

DESIGN & ANALYSIS OF EXTENDED SURFACES

ACMA 6011: Advanced Thermofluid Mechanics

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1. Introduction

The generation of heat within any process may be the result of an intentional interaction or the biproduct of another interaction taking place within the system. Systems where this heat is desired can be seen with heat exchangers and as a biproduct in instances like that of an internal combustion engine or an electric motor. In whatever case, heat transfer is required for the process to function as intended.

This report aims to covers the principles and applications of extended surfaces, in a number of different applications. Within this, the development in fin technology and how new developments will improve upon the technology in years to come.

Using the principles, the balance between the size of the fins and the resulting rate of heat transfer was examined. For this, an analysis was undertaken to show the maximum effective length. Amongst this a series of scenarios in which different materials are compared in their ability to dissipate heat and the required length to ensure the maximum rate of heat transfer.

2. Applications of Cooling Fins

Extended surfaces are common features to any part requiring heat transfer that may be unattainable using the base surface area. Cooling fins occur within an array, having many fin structures cover an area where heat transfer takes place. Fins generally protrude from the surface of the part, with the sole intention of increasing the exposure area with the convective medium (Maatallah, 2021, p.3454). The shape of these fins will vary on a range of factors, including the base geometry of the part and the intended application. Smaller fins may perform poorly in environments where the convective medium has a higher density and flow rate which can deform the fins. Similarly, the design of the fins can serve to interact with other design feature like that seen in electric motors. Electric motors are often air cooled and consist of a number of fins running along the length of the motor housing. A fan attached to the rotor allows air to be pushed through the fins as a form of forced convection (Macangus-Gerrard, 2018, p.11).

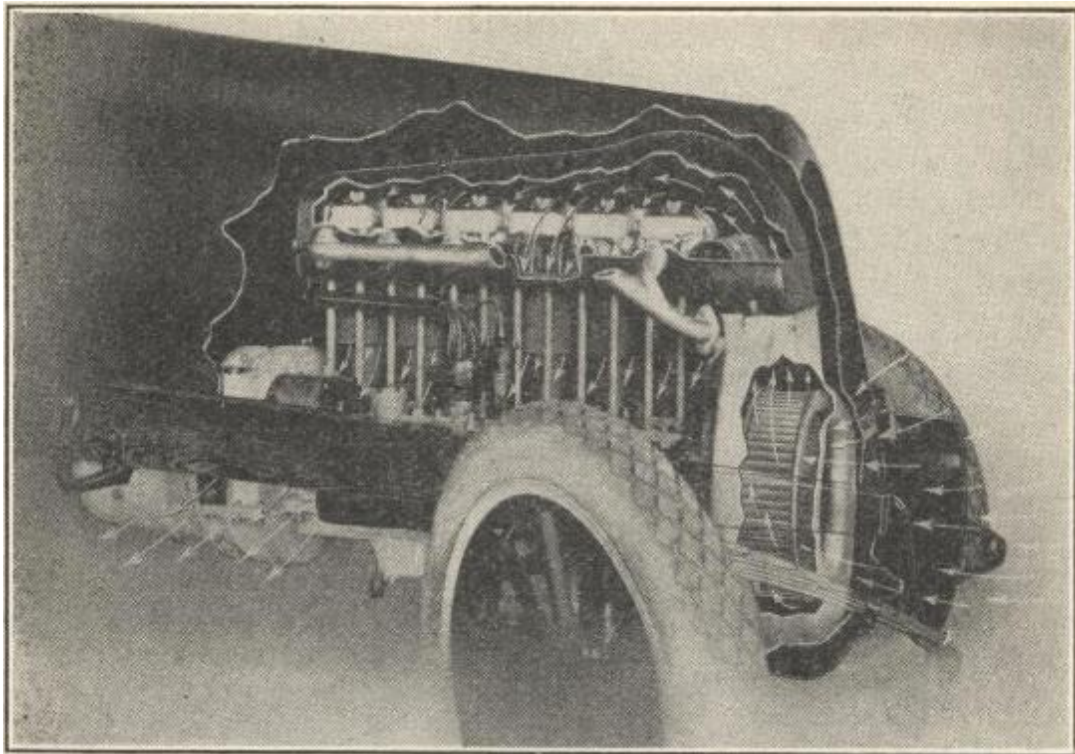


Figure 1: The air-cooling system of the Franklin engine, showing the blower fan at the front of the engine (Grimes, 1923)

In terms of automotive applications, there are numerous areas where heat can be generated and is required to be dissipated, either to maintain performance or prevent damage to the subassembly. The most common of which is the Internal Combustion Engine (Porsche, 2022). Cooling is required for ICEs as functioning without an active form of cooling can damage the engine itself. One of the first instances of air cooling on an internal combustion engine was developed by John Wilkinson of the Franklin Manufacturing company (Scientific American, 1907). Shown in Figure 1, this comprised of a number of fins cast into the head of each cylinder. Later versions of this engine were used in the company's own Franklin car that directed air from the top of the cylinder head to the crankcase, using a crank-mounted blower fan (Grimes, 1923, p.161). Whilst water and, to a lesser extent, oil cooled engines were in use at the same time as these engines, they remained in use within vehicles such as the first-generation Volkswagen Beetle built after 1945 and one of the last production air cooled engines were produced by Citroen (Figure 2) for a number of models until the 1980s (Volkswagen (2024) and Citroën (2015)). It could be seen in Grimes (1923) p.170 that the development of the cooling fins were considered by Franklin. For example, potential optimisation was explored by changing the materials of the fin-carrying head to length and thickness of the individual fins.

In recent years, car engines almost always use a water-cooled system that utilises an air-cooled heat exchanger to provide cooling around the cylinder bores. Only smaller ICEs such as those used in motorcycles and light vehicles use such systems (Neiger, 2024). This is due to the increasing power that is demanded of modern engines along with the emissions regulations, in which an easier to control and an overall more effective system was required (Citroën (2015)).

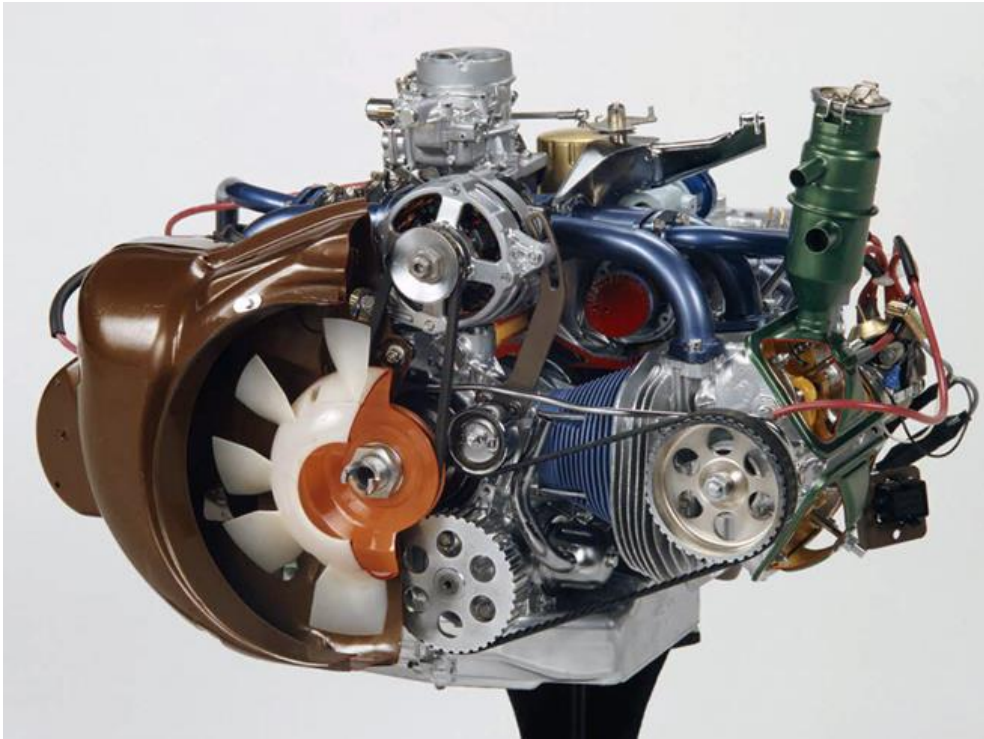


Figure 2: The flat-four, air-cooled engine by Citroën used a forced convection system like the Franklin Engine (Cox, 2005)

Similar to automotive components, fins are used in electronic components where the byproduct of a component's operations is heat. Also, in common with the automotive industry, increasing performance of electronic devices like microprocessors has increased their maximum power output (Parthan, 2023). Maintaining low temperatures of microprocessors serves to maintain performance, though increasing the power output and reducing the dimensions of electronic components makes cooling difficult through economical means like free convection of heat from the surface of the component itself (Sohel Murshed, 2016, p.2). As shown by Zhang *et al.* (2021) p.2, the number of transistors per chip and the overall heat flux has increased since 2000 by over 1000 times and over 3 times respectively.

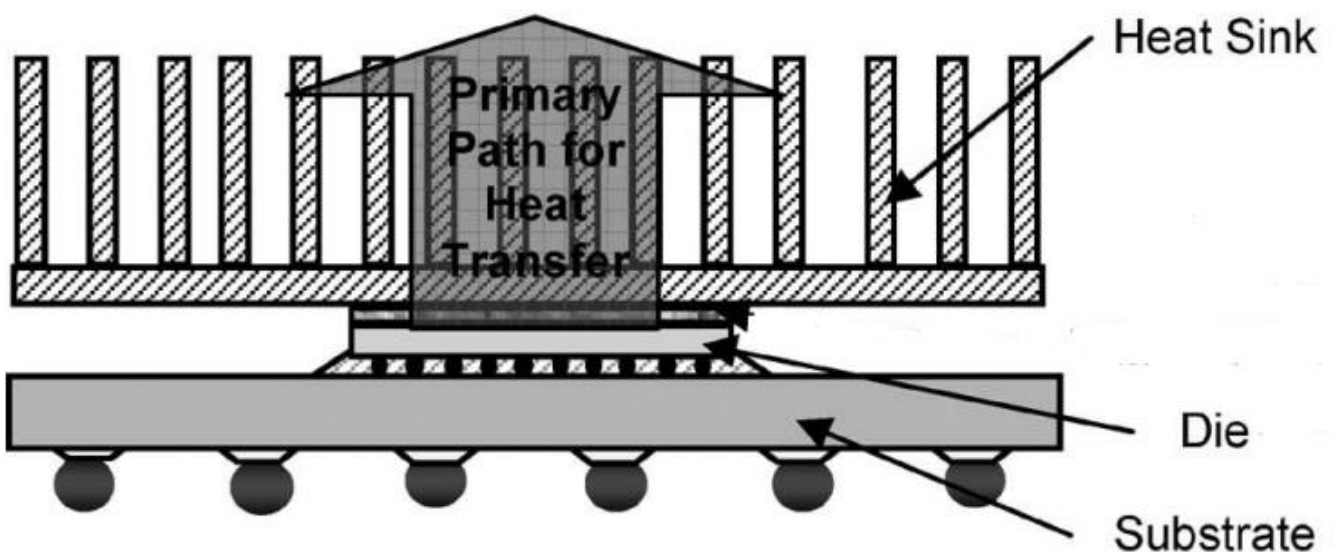


Figure 3: The typical layout of the processor cooling assembly, including the base, die and heat sink (Mahajan, et al., 2006)

To improve upon the rate of heat loss, a number of systems may be used. Some microprocessors use appropriately sized cooling fins to provide adequate heat transfer. This is one of the most common methods by which microprocessors can be cooled. Shown in Figure 3, these are composed of mostly inexpensive aluminium alloys, though can consist of copper alloys for higher performance applications. The geometry of these fins can be extruded, further reducing the cost of this solution (Jogi *et al.* 2023, p.238). More complex geometries require machining,

increasing the cost and waste, though inexpensive compared to more comprehensive solutions. Such cooling fins are attached to the exposed faces of the microprocessor, facing into the open space of the device's case, where heat is dispersed into the surrounding air through natural convection. Often these cooling fins are bonded to the processor using a highly conductive thermal paste, aiming to produce an uninterrupted path to the cooling fins (Magadum and Shamrao, 2015, p.92). This is a simple way to provide effective cooling when compared to zero cooling and is easily adaptable to provide improved cooling depending on the expected output of the processor. However, the effectiveness of these systems rely on the movement of the fluid around the fins. By increasing the flow rate of fluid around the fins, the amount of heat dissipated using the same fins can be increased. Many modern microprocessors use forced convection in the form of a fan. The fan is typically mounted onto the fin array or nearby (Mahajan *et al.* 2006, p.1480). For more powerful processors, the fins are larger, though removed from the processor body but connected using a number of tubes through which heat is dissipated. With the inclusion of one or multiple fans, the fin arrays are smaller than that of passive cooling areas (Sohel Murshed, 2016, p.2).

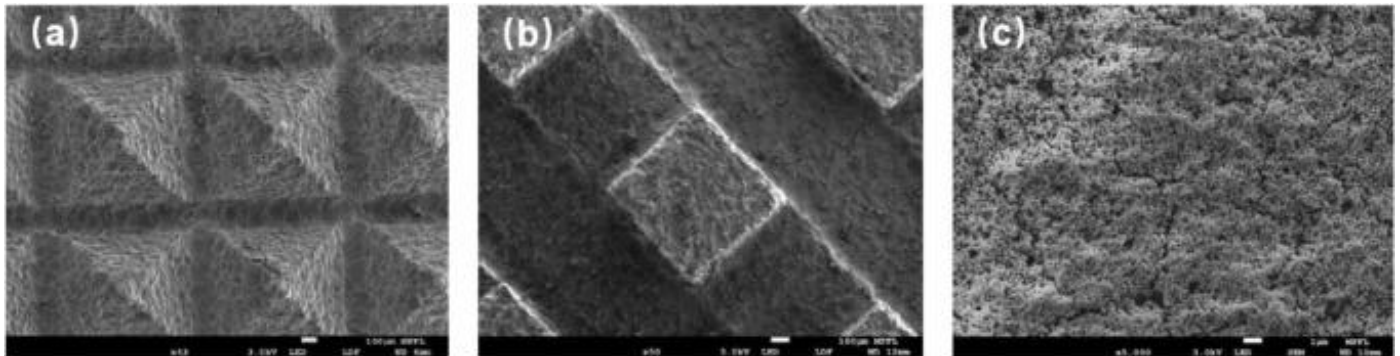


Figure 4: The micro fins used to better dissipate heat on a spray cooling heat sink (Zhang, *et al.*, 2021).

Focus has been placed onto to energy consumption in recent years (Intel, 2023). With natural convection not having the necessary cooling effect and larger fin arrays and cooling fans consuming more energy. As a result, a number of the other cooling methods have been explored (Jogi *et al.* 2023, p.238). Some of these methods includes the use of water cooling, having a larger thermal capacity that of air, either being circulated using a pump or through natural convection. Other methods that have been assessed include other methods like spray cooling in which a series of jets spray coolant onto a conductive plate of aluminium or copper (Zhang *et al.* 2021, p.2). Shown in Figure 4, these plates often consist of micro fin structures that increase the surface area of the evaporative surface like that of other cooling fins. The Coupling methods like this with increased control over the cooling performance by the processor, businesses like (Intel, 2023), aim to improve the cooling performance and energy consumption of processors and wider electronic components.

3. Optimum Fin Parameters

To determine the optimum parameters for the design of a fin, a consistent design was used. In this case, a fin constructed from 2024 aluminium alloy.

In order to determine the optimum result, the heat transfer rate was explored using multiple methods. Such methods includes the adiabatic fin tip method and the infinitely long pin method. This optimisation process aims to prove that the most effective result can be achieved at a value of $mL \approx 2.65$. In order to calculate the heat transfer rate for both the adiabatic fin tip method and the infinite length method, Equations 1 and 2 were used.

$$\dot{Q}_{finite} = \sqrt{hPkA_c}(T_b - T_{\infty}) \tanh(mL) \quad \text{Equation 1.}$$

And,

$$\dot{Q}_{\infty} = \sqrt{hPkA_c}(T_b - T_{\infty}) \quad \text{Equation 2.}$$

Where,

$\dot{Q}_{\infty}$ = Heat transfer rate for adiabatic fin tip (W or J/s)

$\dot{Q}_{finite}$ = Heat transfer rate for adiabatic fin tip (W or J/s)

h = The surface convection coefficient (W/m²k)

P = Cross-sectional perimeter of the fin (m)

K = Thermal conductivity (W/mk)

A_c = Cross-sectional area (m²)

T_b = Temperature at the base of the fin (°C)

T_{∞} = Temperature of the surrounding medium (°C)

m = Fin Parameter (m⁻¹)

L = Actual Fin Length (m)

The optimum value of the mL expression is considered to be 2.65. To prove this, a plot was compiled for these values. The mL expression was plotted against the ratio of the Adiabatic tip heat transfer rate over the infinite heat transfer rate. This is shown in Figure 5.

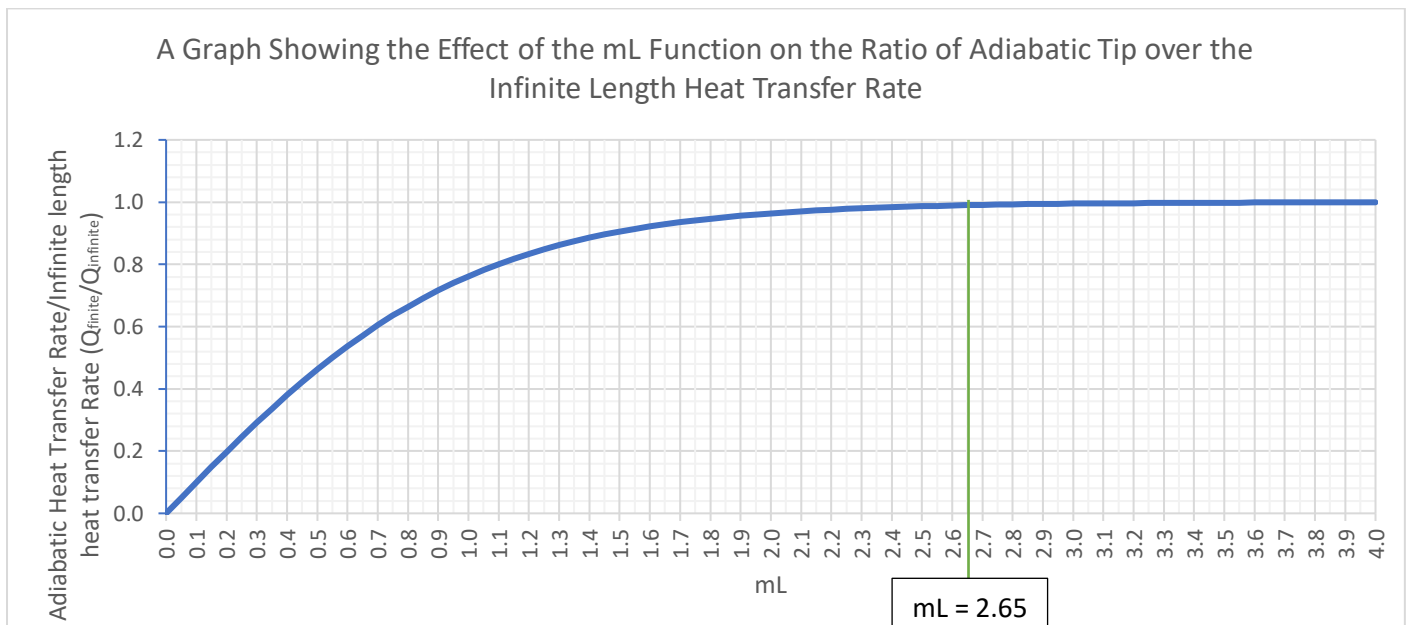


Figure 5: A graph to show the optimum mL value against the heat loss of both infinite and adiabatic tip approximations.

It was shown in the plot the ratio plateaued below the value of 1. When examining the results table in Appendix A, the ratio reached 0.99 at an mL value of 2.65. Exceeding this value, the increase in the value of ratio was minimal, remaining below 1. Hence, exceeding the value of 2.65 would have a minimal impact on the value of heat transfer rate when using either the adiabatic tip method or the infinite length method for determining the optimum fin length.

4. Find Parameter Optimisation

To better understand the limitations of these principles, they were applied to an example using multiple materials. In this case, the geometry consisted of a single round bar, shown in Figure 6.

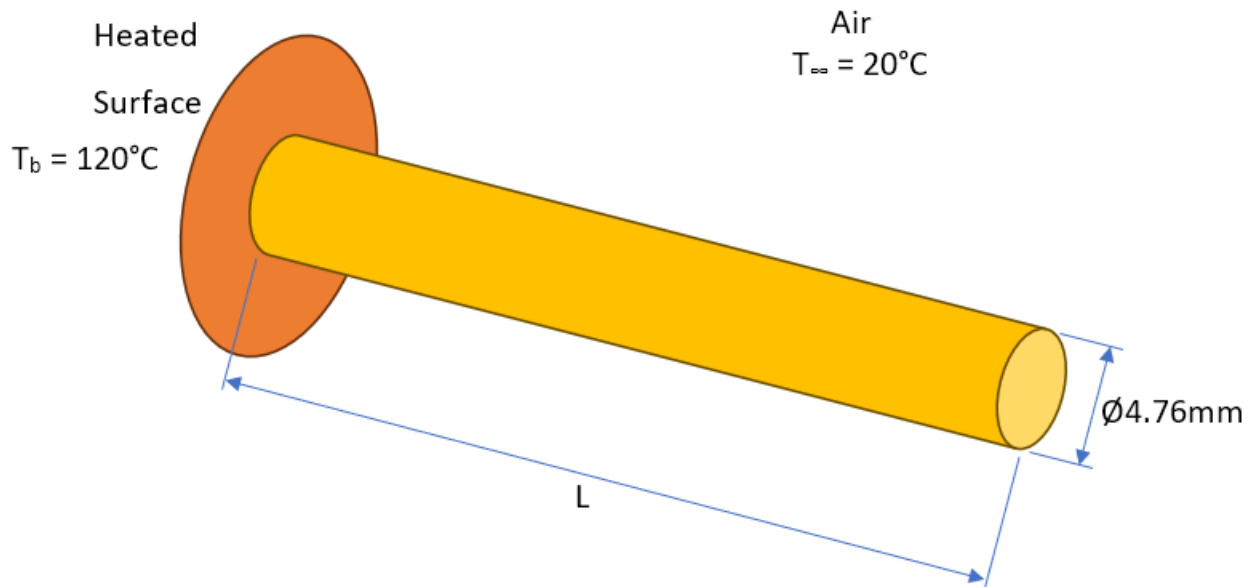


Figure 6: The Layout of the system.

The heat transferred through the heated surface dissipates over the length of the rod. It is assumed that the internal structure of the rod is homogeneous, it was a steady state system, that conduction takes place in one direction and remains constant. The calculations also consider the convective properties of the material's surface. The properties of these materials are shown in Figure 7.

Material Properties		
Material	Convective heat transfer coefficient (h)	Conductive heat transfer coefficient (k)
2024 Aluminium Alloy	30	186
Brass (70Cu/30Zn)	30	99
Copper	15	398
304 Stainless Steel	7.5	16

Figure 7: The data of the material to be used in this analysis.

Considering the properties of the material, the temperature distribution across the length of the rod (L) varied according to their overall performance, shown in Equation 3.

$$T(x) = T_{\infty} + (T_b - T_{\infty})e^{-mx}$$

Where,

x = Distance along the length of the fin (m)

T_{∞} = Ambient temperature of the air (°C)

T_b = Temperature of the base (°C)

m = Performance value of the fin (m^{-1})

Equation 3.

In which m is calculated using Equation 4,

$$m^2 = \frac{hP}{kA_c}$$

Equation 4.

Applying the physical properties of the fin, as shown in Figure 8, allows the temperature to be calculated at any point on the fin.

Fin Properties				
Diameter (mm)	Diameter (m)	Radius (m)	Cross-sectional Area (m ²)	Perimeter (m)
4.76	0.00476	0.00238	1.780×10^{-5}	0.01495

Figure 8: Physical properties of the rod in this analysis.

As a result of this equation, the temperature distribution was calculated. The total distribution of heat was unclear, and the distribution was initially calculated to a length of 400mm. This is seen in Figure 9.

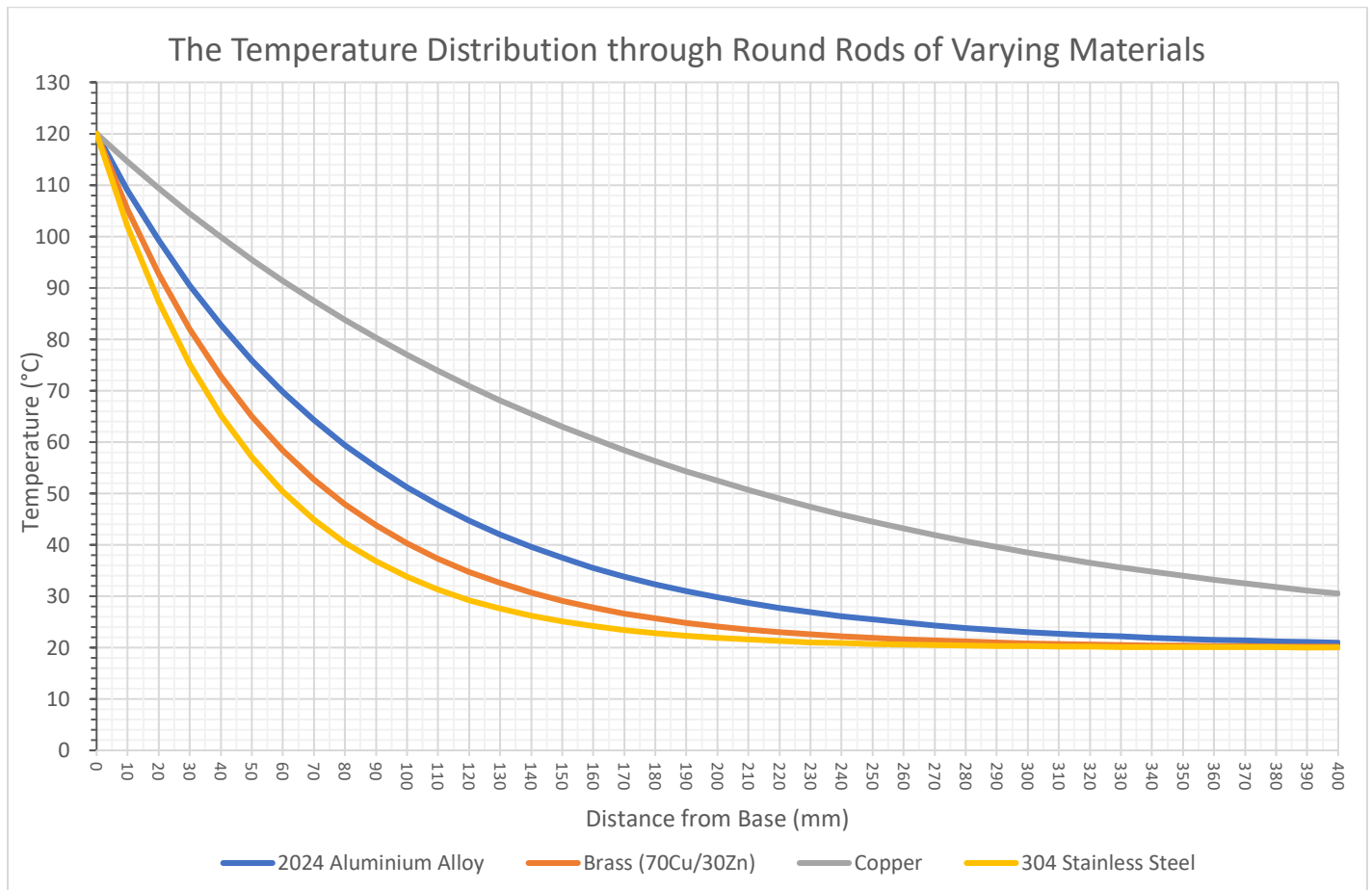


Figure 9: A graph showing the initial analysis of each material to a length of 400mm.

It can be seen immediately that copper experienced a greater temperature distribution, with a tip temperature of 30.5°C. More resistive materials had shown a lower temperature distribution, as seen with the brass and stainless steel. These materials reached a temperature near T_{∞} sooner than that of the aluminium alloy and the copper examples. This serves to indicate that the convective heat transfer coefficient, despite being similar or the same between materials, had no significant impact on the temperature. The conductive heat transfer coefficient, having a much wider variation, also contributed the most to the fin performance value and the subsequent temperature distribution.

To further compare the performance of these materials, the heat loss of each material was calculated using Equation 2. Shown in Figure 10, the copper rod had shown to be the most effective material, being capable of transferring the most energy out of all the materials. As suggested by the temperature distribution and the heat transfer rate, the stainless steel rod was the least effective material.

Material Properties				
Material	Convective Heat Transfer Coefficient (h)	Conductive Heat Transfer Coefficient (k)	Fin Performance Value (m)	Heat Transfer Rate (W)
2024 Aluminium Alloy	30	186	11.6421	3.8534
Brass (70Cu/30Zn)	30	99	15.9577	2.8113
Copper	15	398	5.6277	3.9858
304 Stainless Steel	7.5	16	19.8471	0.5651

Figure 10: Initial results including the fin performance value and corresponding heat transfer rate.

In demonstrating the difference in performance between materials, it could be reasoned that the length of material could be adjusted having little effect on the heat transfer rate. Shown in Section 2, the heat transfer rate remains almost constant when $mL \geq 2.65$. Applying the principle to this instance, the optimum rod length can be found.

If,

$$mL = 2.65 \quad \text{Equation 5.}$$

Then,

$$L = \frac{2.65}{m} \quad \text{Equation 6.}$$

Substituting the values for m for each materials gives the optimum lengths, as shown in Figure 11. As a length of each rod has been defined, the heat transfer rate was calculated using the adiabatic tip method.

Material	Fin Performance Value (m)	Infinite Fin Heat Transfer Rate (W)	Adiabatic Fin Tip Heat Transfer Rate (W)	Optimum Length (m)
2024 Aluminium Alloy	11.6421	3.8534	3.8151	0.2276
Brass (70Cu/30Zn)	15.9577	2.8113	2.7834	0.1661
Copper	5.6277	3.9858	3.9462	0.4709
304 Stainless Steel	19.8471	0.5651	0.5595	0.1335

Figure 11: The results of the optimum length and result heat transfer rate.

Materials with a previously high heat transfer rate and temperature distribution generally utilised a longer length. Due to the greater thermal conductivity, materials like copper and aluminium alloy could obtain higher temperatures at greater lengths. Given this overall higher temperature difference, these rods have a larger effective length than that of stainless steel and brass. With a definite length defined, the temperature distribution was found using Equation 3.

As a result, the temperature distribution of these new values is shown in Figure 12.

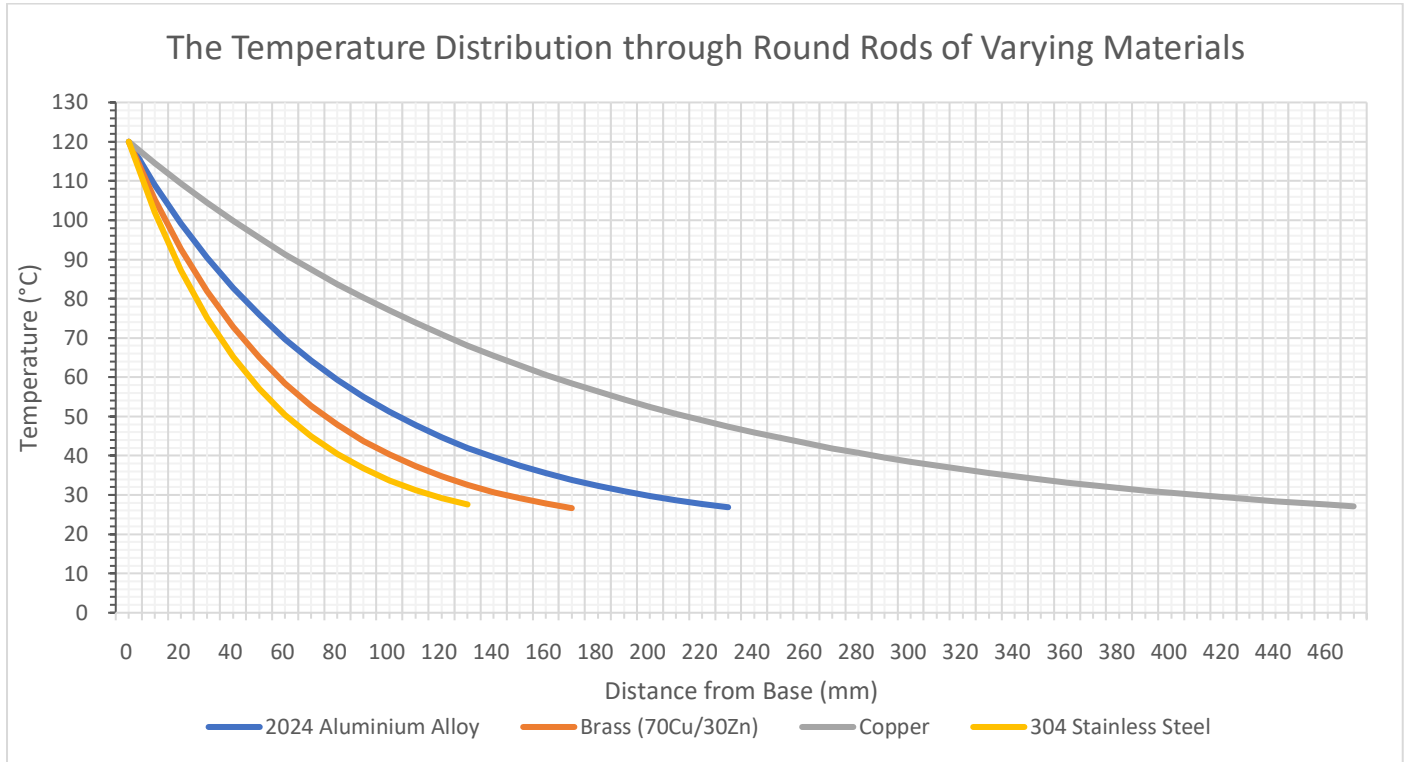


Figure 12: A graph showing the heat distribution at an optimum length of $mL=2.65$.

Copper is shown to have the highest temperature distribution whilst stainless steel is shown to have the lowest. By applying Equation 3 to the optimum rod lengths, each rod terminates with a tip temperature of approximately 34°C. This is 70% of the ambient air temperature, ensuring heat transfer takes place the entire length of the rod. On further inspection, the temperature distribution using the adiabatic tip method is different to that of the infinite tip method. For instance, the infinite length stainless steel rod has a temperature of approximately 27.5°C at 130mm, whilst the adiabatic tip rod has a length of 130mm but yielded a higher temperature.

To maximise the heat transfer rate through the rod, the length is so that the tip has a temperature close to that of the ambient air temperature; though not so long that it offers little to no gain in heat loss. This was demonstrated in Section 2, though did not account for the temperature distribution and approximation with which the temperature is determined. Therefore, a further comparison was made, but increasing the length of the rods until the following condition was met.

$$e^{-mL} < 0.01 \quad \text{Equation 7.}$$

When used within the infinite fin approximation, this translates into a tip temperature of less than 1% of the ambient air temperature. By extending the length of these rods, the value of mL will exceed the optimum value of 2.65. Using 0.01 means that the tip of the fin needs to be within 1% of the ambient temperature. To better understand the approximations that have been used, within this analysis, the heat distribution was found using both approximations to find the temperature along the whole length of the fin, ending when the temperature fell within 1% of the 20°C ambient air temperature. The results for which are shown in Figure 13, along with the calculated values of mL and e^{-mL} to verify the results fit within the desired regions specified.

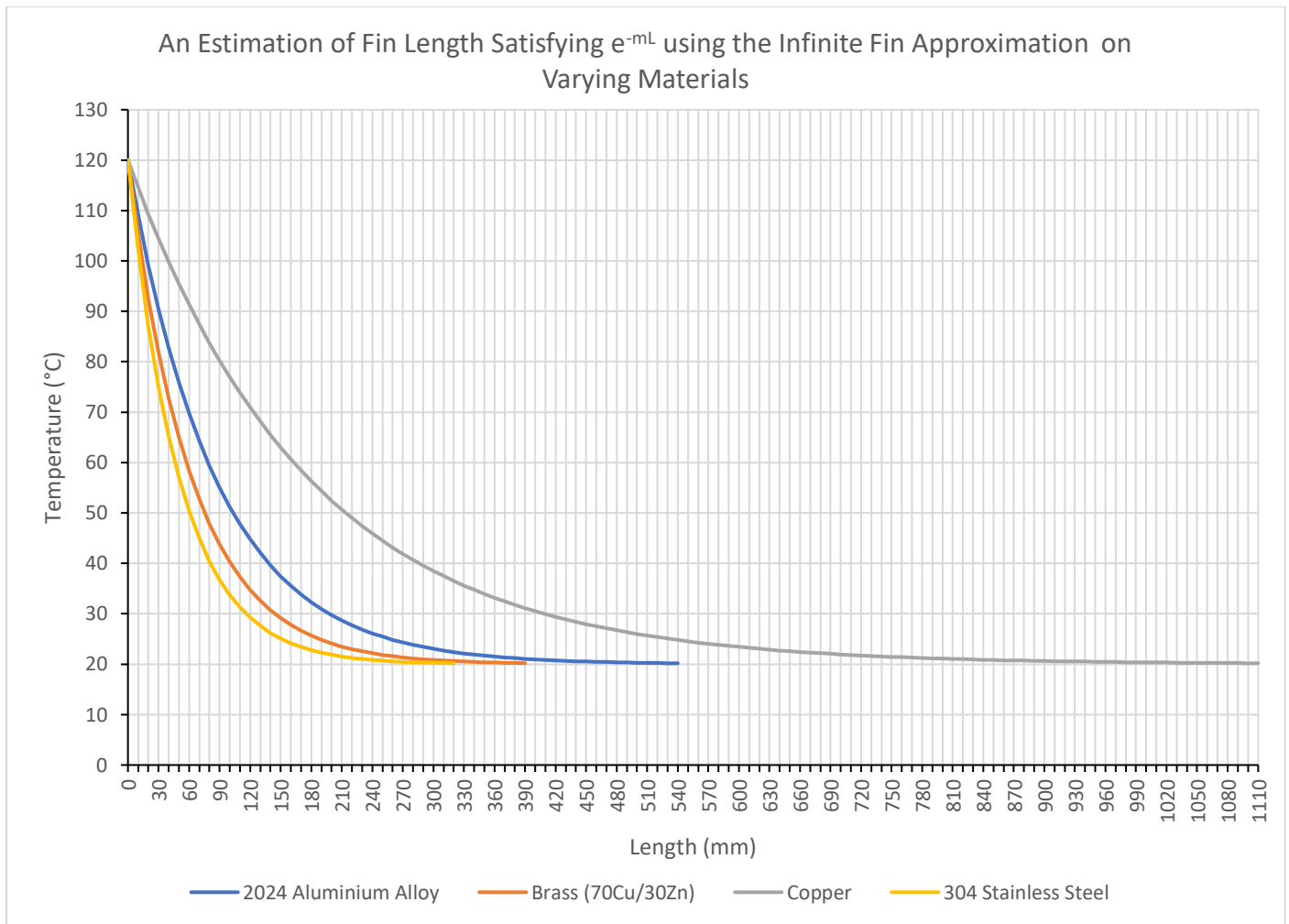


Figure 13: A graph to show the length of the rod if $e^{-mL} > 0.01$, using the infinite length approximation

From the graph, it can be seen that increasing length of the rods had little effect on the temperature distribution passed their respective optimum length. Rather the temperature of each rod quickly plateaued after this point. Subsequently, the additional heat loss afforded by this increased length, would be of little benefit. This was similar to the findings of the Franklin Manufacturing company, that increasing the fin length had limited benefit and was subject to compromise between the length of the fin, the additional weight of the assembly and the manufacturability of the fins themselves. Comparing these results to that of the initial analysis, the heat loss would only be significantly increased for materials with a higher thermal gradient like copper but would otherwise be excessive in length for the remaining materials. Being an infinite length rod, the heat distribution did not account for the condition of the rod end. Therefore, a second analysis was performed using the adiabatic tip method to potentially a realistic response to the same conditions. This is shown in Figure 14.

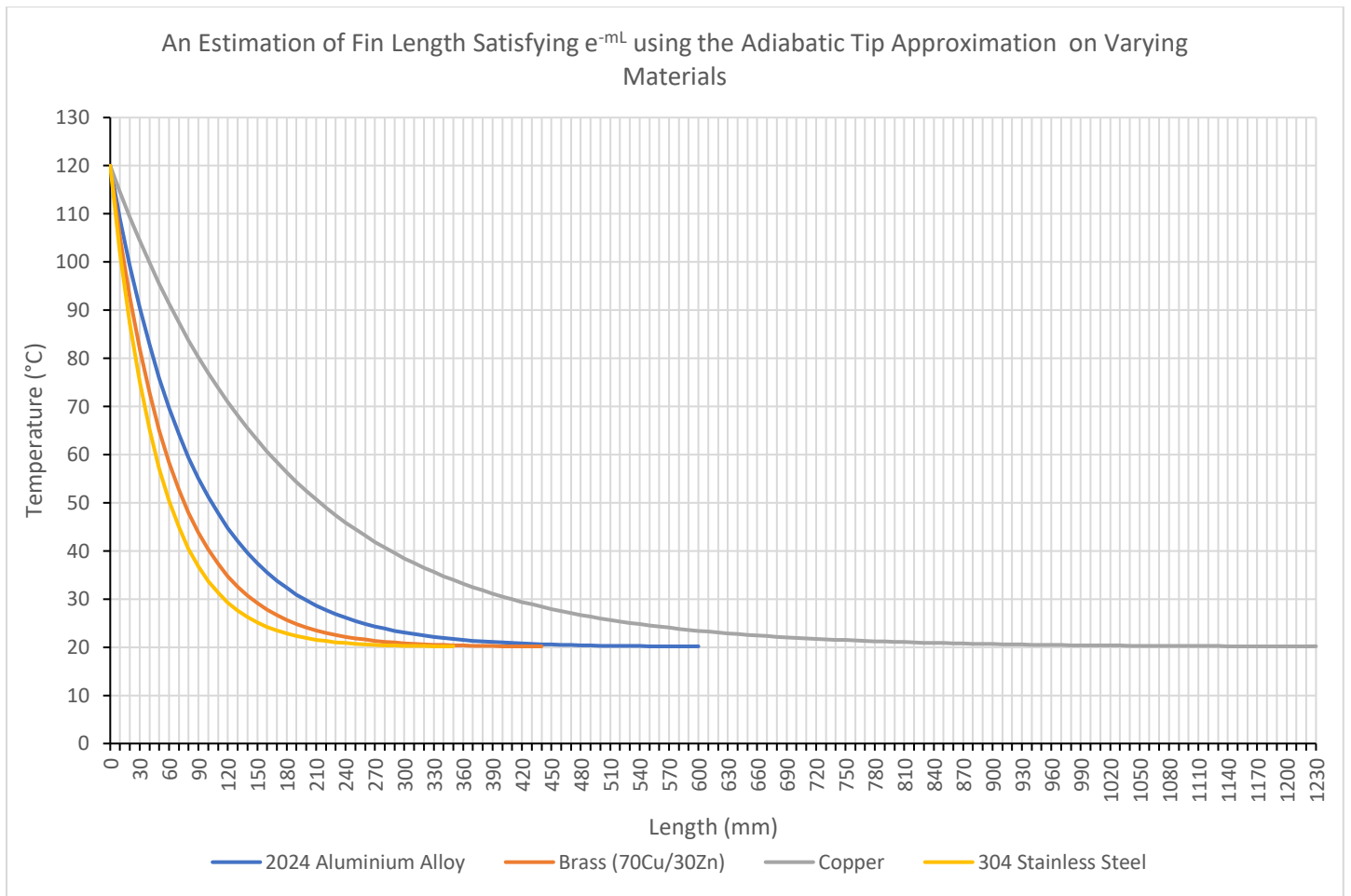


Figure 14: A graph to show the length of the rod if $e^{-mL} > 0.01$, using the adiabatic tip approximation

On initial inspection, the heat distribution appears similar to that of the infinite heat distribution plot. The thermal gradient for each material were almost identical, sharing similar values of temperature where the largest thermal gradient was seen. Yet, the overall length of the rod in the adiabatic tipped examples were longer than that of the infinite length examples. Where the adiabatic fin approximation is typically used in analyses of functional arrays, the length of the fin is often curtailed for the practical purpose previously illuded to. As a further analysis of the validity, the following values for both methods were calculated, this is shown in Figure 15.

Infinite Length Fin Approximation		
Infinite Fin Length Estimation (m)	Infinite Fin Value of mL	Infinite Fin Value of e^{-mL}
0.540	6.287	0.0019
0.390	6.223	0.0020
1.110	6.247	0.0019
0.320	6.351	0.0017

Figure 15: The result values of mL and e^{-mL} to check the validity of this analysis.

The conditions for an accurate approximation of the heat was to that $mL \geq 2.65$. For the infinite length approximation, the value of mL was calculated for each material. Each of these values would vary as the output length varied according the 10mm increment scale of the plot and the differing value of m for each material. Despite this, the mL remained consistent across all materials, and was significantly higher than that of 2.65. Similarly, the value of e^{-mL} was calculated, and each material returned a value considerably lower than the 0.01 threshold originally specified. It was concluded that the length and heat distribution found previously were acceptable.

5. Appendices

5.1 Appendix A – mL optimisation Full Results

mL	$Q_{\text{finite}}/Q_{\infty}$	Q_{finite}	Q_{∞}
0.00	0.0000	0.0000	1.3363
0.05	0.0500	0.0668	1.3363
0.10	0.0997	0.1332	1.3363
0.15	0.1489	0.1989	1.3363
0.20	0.1974	0.2637	1.3363
0.25	0.2449	0.3273	1.3363
0.30	0.2913	0.3893	1.3363
0.35	0.3364	0.4495	1.3363
0.40	0.3799	0.5077	1.3363
0.45	0.4219	0.5638	1.3363
0.50	0.4621	0.6175	1.3363
0.55	0.5005	0.6688	1.3363
0.60	0.5370	0.7176	1.3363
0.65	0.5717	0.7639	1.3363
0.70	0.6044	0.8076	1.3363
0.75	0.6351	0.8487	1.3363
0.80	0.6640	0.8873	1.3363
0.85	0.6911	0.9235	1.3363
0.90	0.7163	0.9572	1.3363
0.95	0.7398	0.9885	1.3363
1.00	0.7616	1.0177	1.3363
1.05	0.7818	1.0447	1.3363
1.10	0.8005	1.0697	1.3363
1.15	0.8178	1.0927	1.3363
1.20	0.8337	1.1140	1.3363
1.25	0.8483	1.1335	1.3363
1.30	0.8617	1.1515	1.3363
1.35	0.8741	1.1680	1.3363
1.40	0.8854	1.1831	1.3363
1.45	0.8957	1.1969	1.3363
1.50	0.9051	1.2095	1.3363
1.55	0.9138	1.2211	1.3363
1.60	0.9217	1.2316	1.3363
1.65	0.9289	1.2412	1.3363
1.70	0.9354	1.2500	1.3363
1.75	0.9414	1.2579	1.3363
1.80	0.9468	1.2652	1.3363
1.85	0.9517	1.2718	1.3363
1.90	0.9562	1.2778	1.3363
1.95	0.9603	1.2832	1.3363
2.00	0.9640	1.2882	1.3363
2.05	0.9674	1.2927	1.3363
2.10	0.9705	1.2968	1.3363
2.15	0.9732	1.3005	1.3363
2.20	0.9757	1.3038	1.3363
2.25	0.9780	1.3069	1.3363

2.30	0.9801	1.3097	1.3363
2.35	0.9820	1.3122	1.3363
2.40	0.9837	1.3144	1.3363
2.45	0.9852	1.3165	1.3363
2.50	0.9866	1.3184	1.3363
2.55	0.9879	1.3201	1.3363
2.60	0.9890	1.3216	1.3363
2.65	0.9901	1.3230	1.3363
2.70	0.9910	1.3242	1.3363
2.75	0.9919	1.3254	1.3363
2.80	0.9926	1.3264	1.3363
2.85	0.9933	1.3274	1.3363
2.90	0.9940	1.3282	1.3363
2.95	0.9945	1.3290	1.3363
3.00	0.9951	1.3297	1.3363
3.05	0.9955	1.3303	1.3363
3.10	0.9959	1.3309	1.3363
3.15	0.9963	1.3314	1.3363
3.20	0.9967	1.3318	1.3363
3.25	0.9970	1.3323	1.3363
3.30	0.9973	1.3326	1.3363
3.35	0.9975	1.3330	1.3363
3.40	0.9978	1.3333	1.3363
3.45	0.9980	1.3336	1.3363
3.50	0.9982	1.3338	1.3363
3.55	0.9984	1.3341	1.3363
3.60	0.9985	1.3343	1.3363
3.65	0.9986	1.3345	1.3363
3.70	0.9988	1.3346	1.3363
3.75	0.9989	1.3348	1.3363
3.80	0.9990	1.3349	1.3363
3.85	0.9991	1.3351	1.3363
3.90	0.9992	1.3352	1.3363
3.95	0.9993	1.3353	1.3363
4.00	0.9993	1.3354	1.3363

Appendix 1: The results of the analysis in Section 2, showing the value of Q_{finite}/Q_{∞} at the optimum value of $mL=2.65$

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